REPORT DOCUMENTATIO

n Approved
B No. 0704-0188

REPORT SECURITY CLASSIFICATION
Unclassified

AD-A230 840

SECURITY CLASSIFICATION AUTHORITY

DECLASSIFICATION / DOWNGRADING SCHEDULE

unlimited

PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)

NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
Georgia Institute of Technology		

ADDRESS (City, State, and ZIP Code)	7b. ADDRESS (City, State, and ZIP Code)
School of Aerospace Engineering Georgia Institute of Technology Atlanta, Georgia 30332	

NAME OF FUNDING/SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
Office of Naval Research		N00014-90-J-1657

ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS			
800 North Quincy STreet Arlington, VA 22217-5000	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.

TITLE (Include Security Classification)
"Investigation of Research Needs for Underwater Explosions"

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TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 1/1/90 TO 12/31/90	90-12-31	

SUPPLEMENTARY NOTATION

COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	explosions, anti-submarine warfare, detonation, bubbles. (such as aluminum)

ABSTRACT (Continue on reverse if necessary and identify by block number) and the explosion gases and explosion effects they create.)

→ By means of laboratory visits, personal interviews and literature study, research needs in the area of conventional weapons underwater explosions were identified. The capacity of universities to enter into this research was also assessed. Several areas of detonation physics and chemistry were identified as needing research, especially for nonideal, composite explosives. Similarly the behavior of the underwater explosion bubble was found to be poorly understood in detail. Of particular significance was the lack of understanding of metal ingredient behavior in both explosives and in steam explosions. It was found that while universities can indeed contribute to understanding and analysis of various processes, the detonation facilities of national and government laboratories must be brought into the research effort. Weapons effects on submarine hulls is also addressed in this effort.

DISTRIBUTION/AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	unclassified
NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL

Form 1473, JUN 86   Previous editions are obsolete.   SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

INVESTIGATION OF RESEARCH REQUIREMENTS
FOR UNDERWATER EXPLOSIONS

Final Report

to

Office of Naval Research

under

Grant No. N00014-90-J-1657

by

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Accession For	
NTIS GRA&I	☒
DTIC TAB	☐
Unannounced	☐
Justification	

By	
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Availability Codes	
Dist	Avail and/or Special
A-1	

Warren C. Strahle
Principal Investigator

INTRODUCTION

This Final Report consists of a set of viewgraphs with a preceding page for each viewgraph as an explanatory exposition. The viewgraphs which follow were presented to the Contract Monitor, Dr. Richard S. Miller, at ONR on December 18, 1990. This briefing constituted the final output on the program entitled "Investigation of Research Requirements for Underwater Explosions".

The purposes of the program were to, first, determine the research needs in the area that would fit under the 6.1 category of government research funding and, second, to determine which parts of the 6.1 community could contribute. It was generally found that the University part of this community could, indeed, contribute significantly to research in this area. However, it is deemed necessary to include Government and National Laboratories in a coordinated effort because of the condensed phase detonation facilities possessed by these laboratories.

It is recommended that an Accelerated Research Initiative be formed to attack the areas of scientific understanding shown in these viewgraphs to be in need of such work.

A TARGET

Shown is a Soviet Oscar class guided missile submarine, which is one potential troublesome target. A double-hulled device, there is considerable controversy as to whether a non-contact weapon can kill this submarine. Concerns like this have given impetus for the formation of a research initiative in underwater explosions.

SOVIET OSCAR
CLASS SSGN
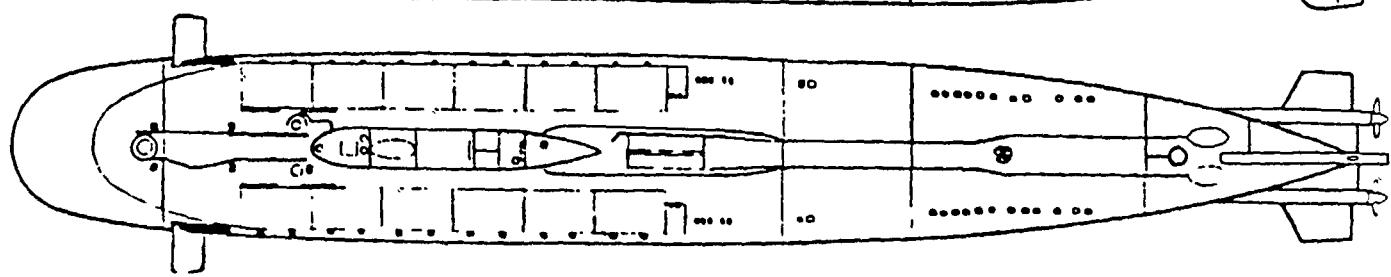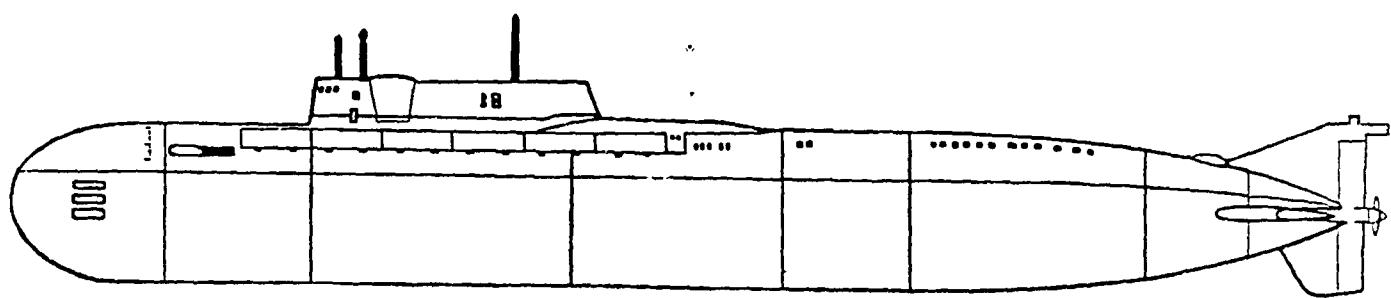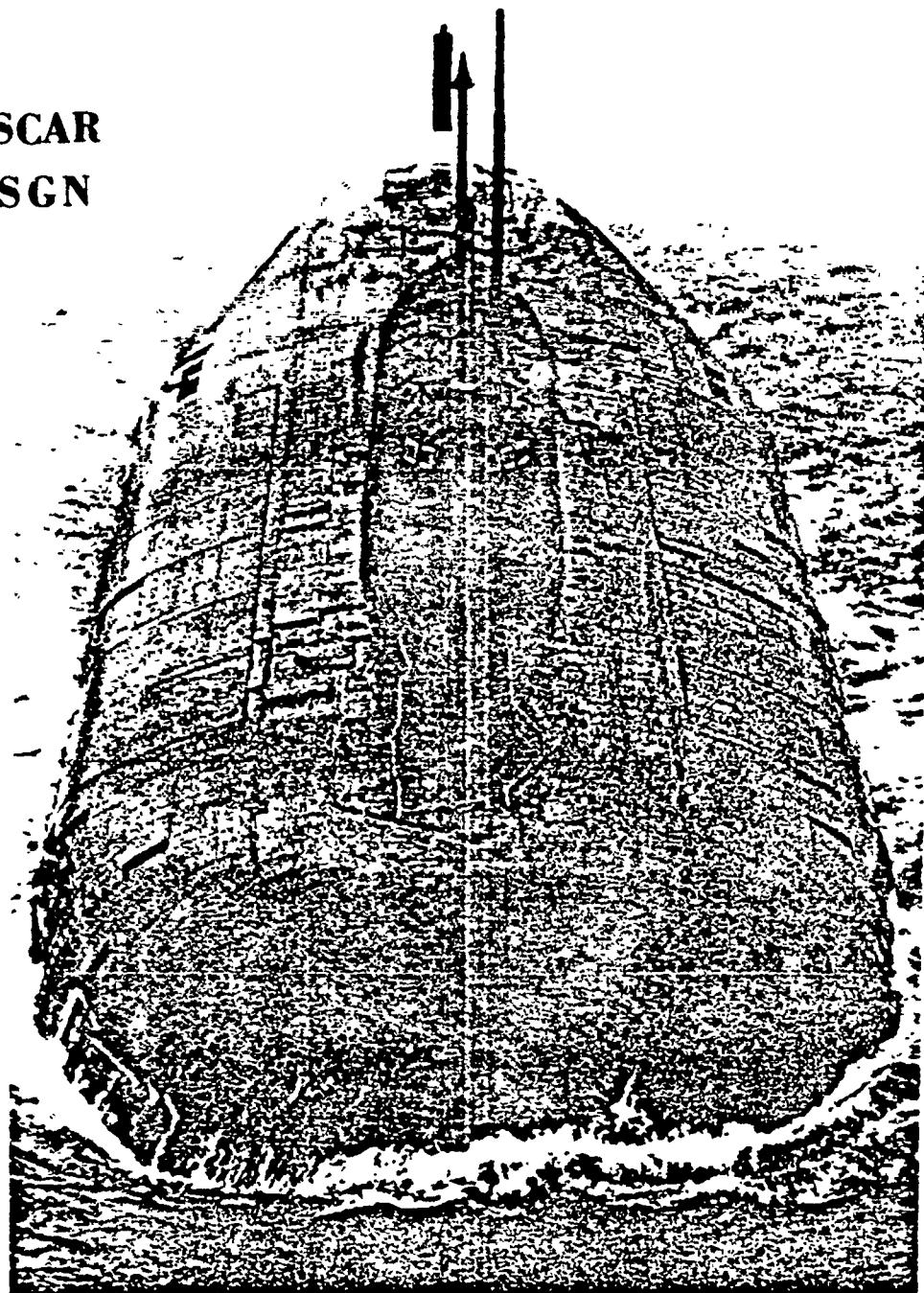
TASK INTERVIEWS

Shown are the principal people interviewed and the laboratories visited during the course of this program. Facilities were inspected and research ideas were explored. In addition, over 100 references were collected and studied during the course of the program. It should be mentioned that all people were highly cooperative and were enthusiastic concerning the possibility of a future directed effort in this area.

TASK INTERVIEWS AND VISITS

- LABORATORIES
  NSWC – R. Doherty*, G. Harris*, T. Farley, D. Hinely, J. Connor, D. Lehto,
  W. Szymczak, D. Cichra, J. Forbes
  LLNL – W. Tao*, C. Tarver, B. Bowman*
  SANDIA Albuquerque – D. Beck*, M. Berman*
  NRL – E. Oran, J. Boris

- UNIVERSITIES
  RPI – J. Shepherd*
  Illinois – H. Krier*
  Notre Dame – J. Powers
  Penn State – K. Kuo
  Michigan – M. Sichel*
  UC Irvine – W. Sirignano*
  Georgia Tech – E. Price*

- Material Received from Other Sources
  NRL – R. Ford; Washington State Univ. – Y. Gupta; McGill Univ. – J. Lee;
  NOS Indian Head – E. Baroody; Univ. of Illinois – M. Brewster

Notes: 1. * denotes people present at Atlanta Workshop
2. Over 100 references collected on underwater explosion topics
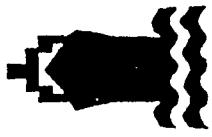
WHAT'S NEW

A workshop was conducted, chaired by the PI, in August, 1988 to explore the limits of understanding at that time in the area of underwater explosions. The current effort was to see what had transpired since that time in research and technology. Following figures will amplify on the areas mentioned in this viewgraph.

WHAT'S NEW

OR WAS OMITTED AT THE ATLANTA WORKSHOP

- EVIDENCE OF EARLY TIME REACTIONS OF THE ALUMINUM

- ALUMINUM EXPLOSIONS IN WATER

- PROGRESS IN UNIFICATION OF THE FIELDS OF STEAM EXPLOSIONS, METAL-WATER EXPLOSIONS AND CHEMICAL DETONATIONS

- CODE DEVELOPMENTS FOR BUBBLE DYNAMICS AND DAMAGE

- EVIDENCE OF THE EXTREME IMPORTANCE OF RAYLEIGH-TAYLOR INSTABILITY IN BUBBLE BEHAVIOR AND METAL-WATER EXPLOSIONS

- MULTIPLE PHASE DETONATION ANALYSIS TECHNIQUES

- PRESSURE SENSOR WORK

- MASSIVE CORRELATIONS OF PAST UNDERWATER EXPLOSIONS WORK

- NEW METHODS OF ESTIMATION OF HEAT OF DETONATION

- UNIVERSITY-NATIONAL LABORATORY COLLABORATION
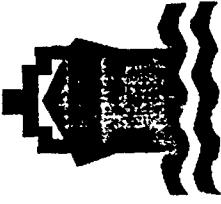
VULNERABILITY AND DAMAGE

Shown are a short time trace of the water shock wave pressure and a long time trace containing the shock and the pressure due to several bubble periods of expansion and contraction. In the shock trace, two shocks may be seen. In principle, an infinite number of trailing shocks would be seen, of ever diminishing strength. The trailing shocks are caused by an impedance mismatch (to be discussed later) between the detonation emanating from the charge and passing into the water.

The peak pressure in the shock is considerably larger than that due to the bubble oscillations, but typically the impulse delivered by the shock is about the same as delivered by the first bubble pulse. Damage mechanisms include the shock impact on the target, the impulse delivered by the bubble pulses, hull oscillation (whipping) induced by the pressure field (unsteady) from the bubble oscillations, and impact forces of a jet produced by the bubble if the bubble is sufficiently close to the target. In this figure R is slant range from the explosion center to the target and A_{max} is the maximum bubble radius on its first expansion.

Since the bubble migrates upward, due to gravity, positioning of the explosion is critical. The deeper the explosion, the less the migration speed.

VULNERABILITY AND DAMAGE

- SHOCK AND BUBBLE CHARACTERISTICS

  Shock has higher peak pressure than the bubble causes but impulse is about the same for both

  Secondary shock caused by impedance mismatch between the initial detonation wave and water
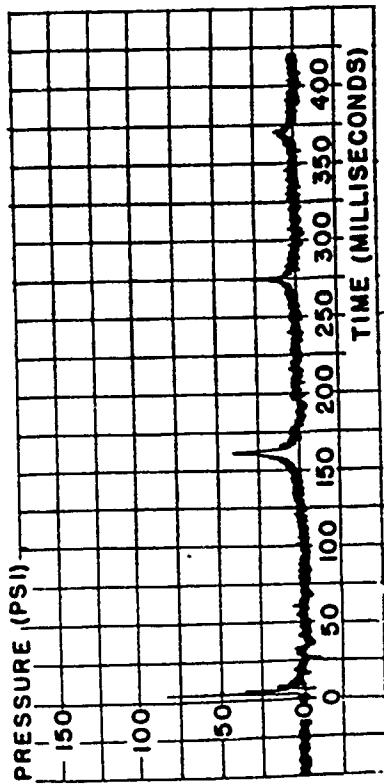
  Unsteady and spatially variant pressure field caused by bubble (long period) causes bending (whipping) of target hull

  If bubble is close enough to target the bubble will form a high momentum liquid jet directed at target with maximum damage for R/A_{max} at about 0.8

TYPICAL PRESSURE TRACES

SHOCK

SHOCK AND BUBBLE
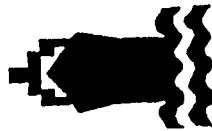
VULNERABILITY AND DAMAGE (cont.)

The ability of the shock wave to impose damage is usually measured by a number called the "shock factor", as shown. The square of this factor is the ratio of explosive energy to the square of distance from the charge and is the factor to which shock wave energy is proportional in <u>linear acoustics</u>. It is a fact that after about only 10 charge radii the shock propagation follows linear acoustics as opposed to strong shock (blast wave) propagation laws. The latter would have shock pressure proportional to energy divided by range^3. The reason for following nearly acoustic physics is the weak compressibility of water; although the overpressures may be quite high compared with ambient pressure, the density does not change very much.

At first, shock wave energy seems strange as a correlating parameter for damage, as opposed to shock impulse, which would scale differently than shock energy. The reason appears to be that at reasonably low pressures, where impulse controls, the target metal resists bending. However, at higher pressures the metal stress plays no role and the metal is being purely accelerated. As a consequence, a given damage value would follow roughly a constant value of impulse times pressure, which scales as the square of the shock factor.

The hull whipping mechanism of damage can be reasonably well calculated by bubble-hull interaction hydrocodes coupled with a model of the ship (target) dynamics. Calculation of this effect appears to be in hand, provided intelligence information on the structure of the target is known.

Bubble impulse and bubble jet damage are highly empirical at the current time, primarily because modelling and computing of the bubble behavior are not in an advanced state. More concerning the bubble behavior will come later.

The relative importance of the various kill mechanisms depends on not only the target type but the explosive depth, range and type. Given the target, it would be a good goal to have control over the characteristics of the shock and the bubble.

VULNERABILITY AND DAMAGE (cont.)

- SHOCK WAVE DAMAGE
  Measured by shock factor $\sqrt{W}/R$, where W is the charge weight(lb) in units of TNT equivalent and R is slant range(ft). A typical magnitude required for compartment flooding is about .75.

  Shock wave parameter is interesting since it follows a scaling law for shock wave energy in the <u>acoustic</u> limit. Probably follows because of a constant damage hyperbola in peak pressure-impulse coordinates ($p \cdot I =$ a constant) and is a tradeoff between metal acceleration and bending.

- HULL WHIPPING
  Modelling consists of bubble-hull interaction hydrocodes coupled with mass-spring ship models to determine critical deflections.

- DIRECT BUBBLE AND BUBBLE JET DAMAGE
  Bubble jet effects highly empirical at the current time, but codes are under development.

- UNCERTAINTIES IN PREDICTION
  What constitutes a kill?   Code validation.
  Where are the components on an enemy ship?   Exact construction?
  Prediction code sophistication.

- IT WOULD BE NICE TO BE ABLE TO "DIAL A SHOCK AND DIAL A BUBBLE"
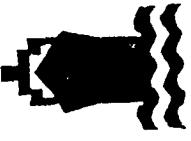
DETONATION AND BUBBLE PHYSICS AND CHEMISTRY

This is a header for several of the following charts.
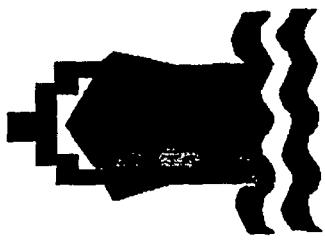
# DETONATION AND BUBBLE

PHYSICS AND CHEMISTRY

THEORETICAL HUGONIOTS

The next three charts are to be taken as a group. They each consist of three curves. First, there is the Hugoniot curve, in pressure-particle velocity coordinates, for a shock wave in water. Then there are two curves, each for different solid explosive densities, giving the Chapman-Jouget pressure and particle velocity for various values of the enthalpy of detonation (q) of the explosive. The water shock is empirical, but the detonation calculations are theoretical, assuming perfect gas products with some condensed phase material, the mass fraction of condensed phase products being denoted by Y_s. The trick in assuming perfect gases and still getting good numbers is in the choice of the ratio of specific heats, an effective value of which is about 3, herein chosen as 3.0. The first chart is for $Y_s=0$, the second is for $Y_s=.3$ and the third chart is merely an overlay of the first two charts.

The purpose here is to emphasize certain properties of solid phase detonations and the process of the transfer of the detonation energy to the water shock. First, there are the well known properties that the Chapman-Jouget pressure of the detonation increases as the heat of detonation and the solid phase density increase, the increase being linear in both. Less well known is the fact that if solid or liquid particles are formed in the detonation products the C-J pressure drops, because of removal of mass from the gas phase. Not well appreciated at all, however, is that at a fixed detonation pressure there is a mismatch between the particle velocities behind the detonation and the water shock. This mismatch occurs for all conventional explosives and, as a consequence, there cannot be a smooth transfer of the detonation into the water. A reflection must occur at the explosive-water interface which has as a consequence that the full C-J pressure is not transmitted into the water and a wave is reflected into the remaining detonation bubble. For a given density and q, the mismatch is minimized for $Y_s>0$, but the pressure transmission into the water is lowered.

Given that the explosive is also encased, there is a further reflection back into the explosive bubble and reduction of pressure transmission into the water. The net effect of these impedance mismatches is ultimately the creation of irreversible processes in the bubble, lowering the effectiveness of the explosion. On the other hand, a lower water shock pressure lowers the dissipation in the water shock.

THEORETICAL HUGONIOTS

Pressure (kbar) vs Particle Velocity (m/s)

- ▲ Water Hugoniot
- ● Rho = 1500 kg/m^3, Ys = 0
- ■ Rho = 2000 kg/m^3 Ys = 0

q = 1000 cal/gm

THEORETICAL HUGONIOTS

▲ Water Hugoniot

o Rho = 1500 kg/m^3 Ys = 0.3

□ Rho = 2000 kg/m^3 Ys = 0.3

q = 3000 cal/gm

q = 1000 cal/gm

Pressure (kbar)

Particle Velocity (m/s)

THEORETICAL HUGONIOTS

Water Hugoniot

▲ Rho = 1500 kg/m^3, Ys = 0

● Rho = 2000 kg/m^3, Ys = 0

■ Rho = 1500 kg/m^3, Ys = 0.3

× Rho = 2000 kg/m^3, Ys = 0.3

+

q = 3000 cal/gm
Ys = 0.3

q = 1000 cal/gm
Ys = 0
Ys = 0.3

Particle Velocity (m/s)

Pressure (kbar)

1000   750   500   250   0

1000   2000   3000   4000
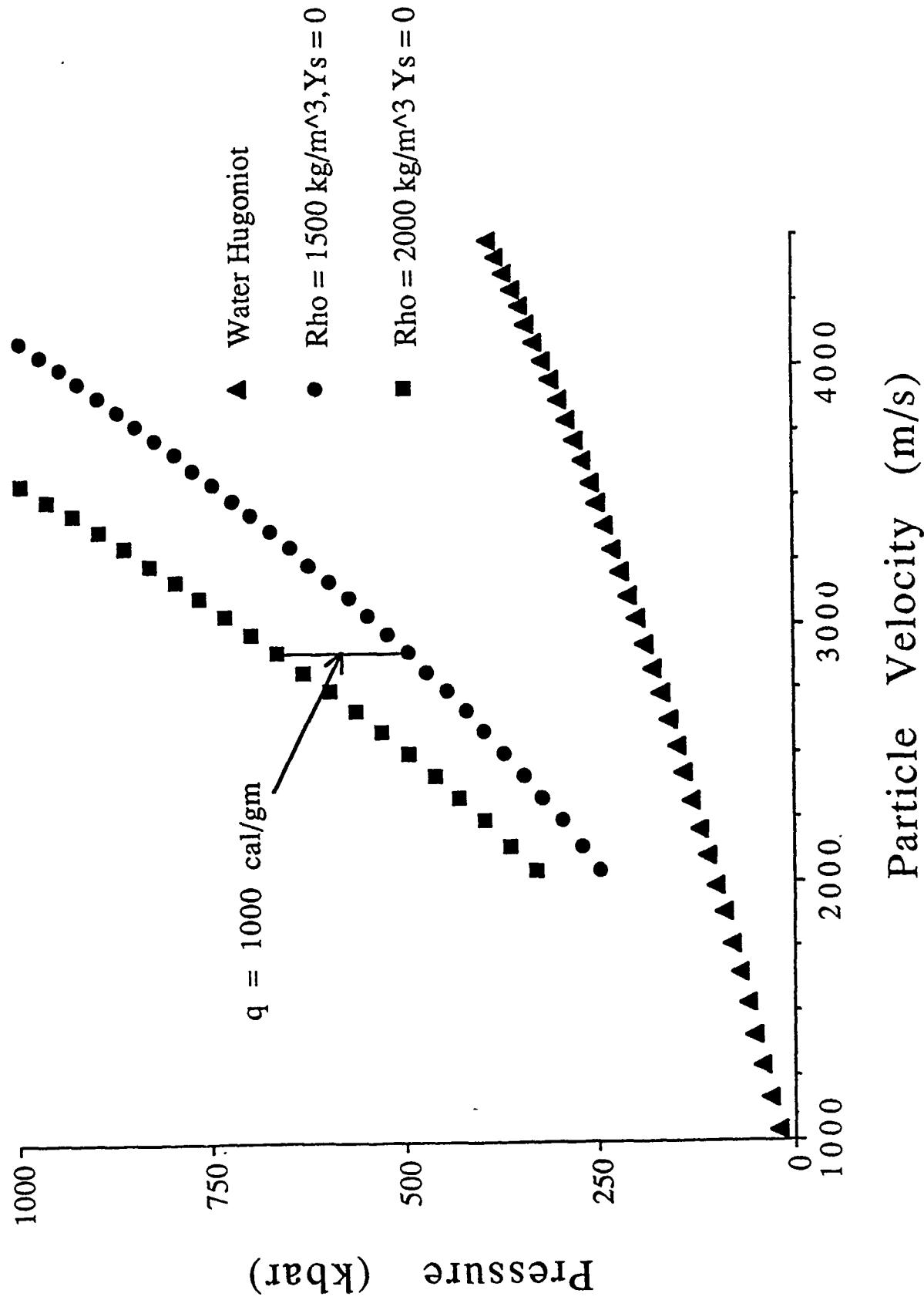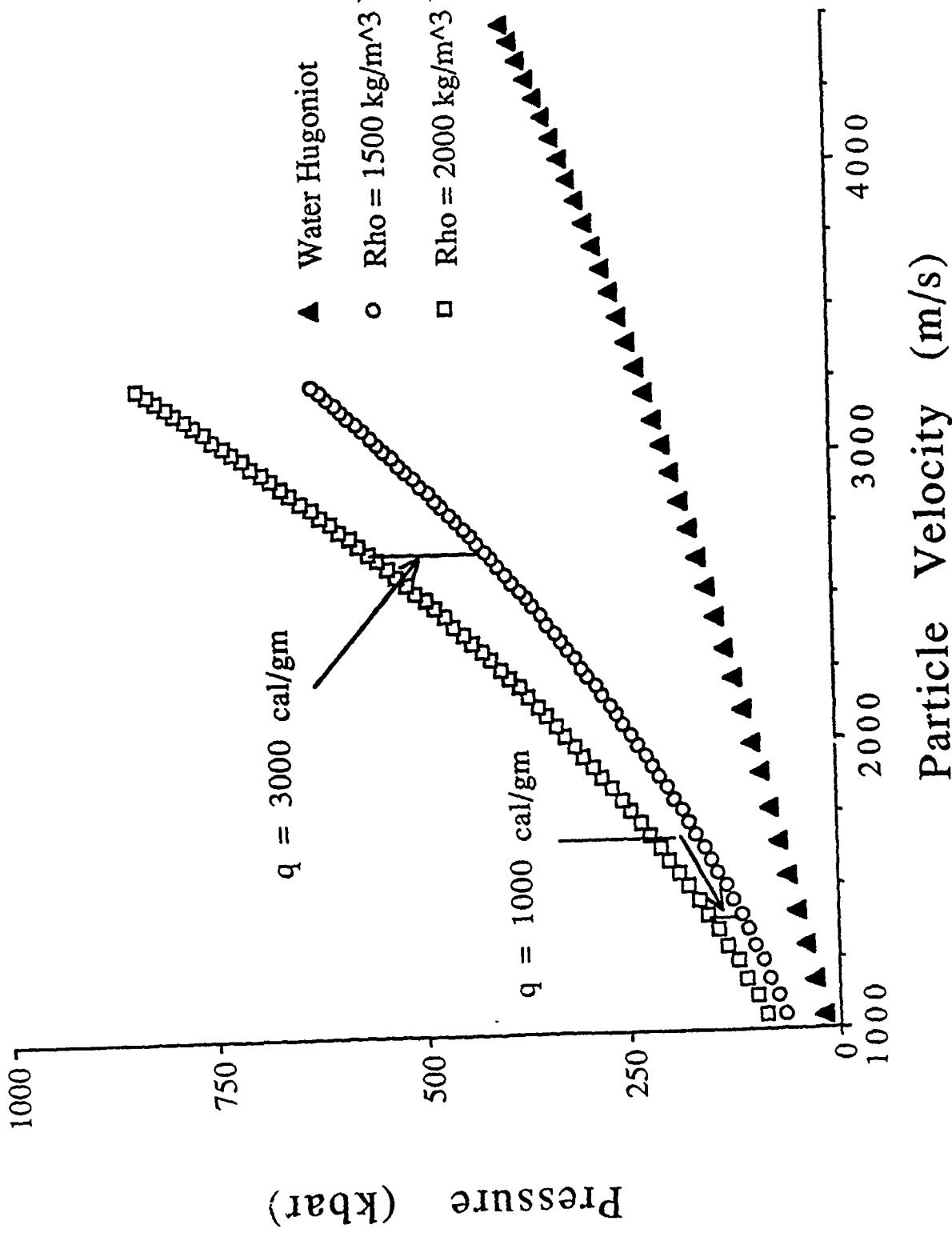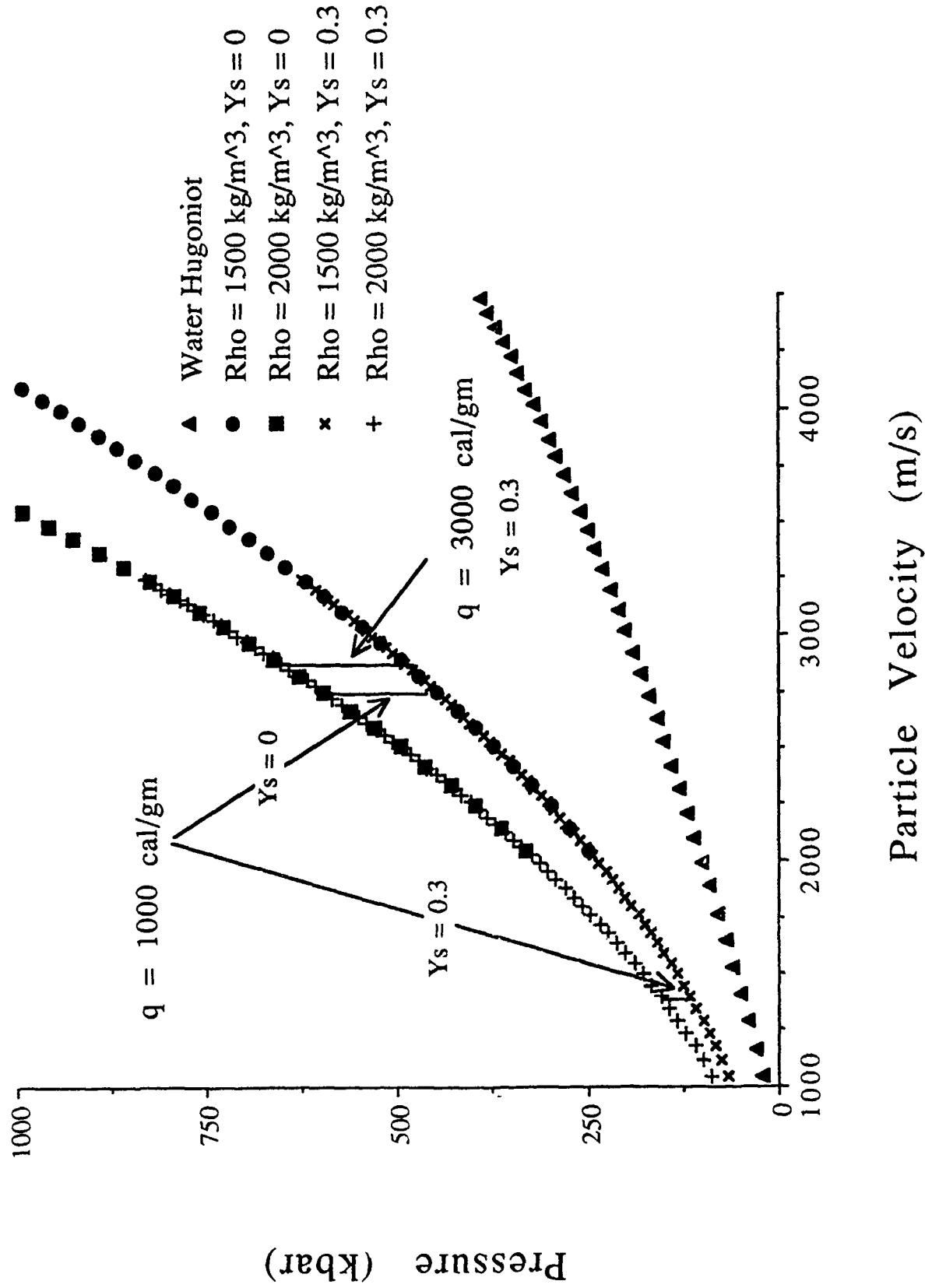
## TIGER CALCULATIONS

These are calculations made using the computer code TIGER, a standard explosion code, for actual explosives (and one contrived one). The coordinates of the graph are the same as those of the three preceding figures. Assumed in the calculations is chemical equilibrium at the C-J plane, but high pressure equations of state (EOS) are employed. At the left end of each of the lines intersecting the water shock Hugoniot for the different explosives is the C-J point for that explosive. The lines are the isentropes along which the bubble products expand to make a match with the water shock. The intersection gives the shock properties for the water. Although these calculations are representative of the actual state of affairs, it should be borne in mind that the equilibrium assumption overstates the pressures achievable, because the condensed phase products, especially, probably are not completely formed.

As seen in the prior three figures, addition of Al to an explosive, causing the condensed phase product Al_2O_3, lowers the water shock pressure (compare pure RDX to 85% RDX - 15% Al). At first glance this would appear to be a bad effect, but it will be seen that it is actually beneficial to the efficacy of the explosion. Note the Fleet explosive (N103), which is aluminized, has a lower water pressure than those from the RDX explosives. Yet it works out that this is beneficial (note how closely the Fleet explosive is impedance matched to the water). Ammonium perchlorate is by itself a relatively poor explosive, but it releases a lot of oxygen which may be taken advantage of by the addition of aluminum. Ammonium perchlorate is an ingredient in N103.

A contrived explosive is the 50% Al - 50% water mixture. The mixture of cold aluminum metal and cold liquid water is not actually detonable, but TIGER does not know this and can compute the explosion result if equilibrium were achieved. As shown, although there is a strong impedance mismatch, this would be a respectable explosive. Now ask what would happen if the water were free; that is, if only aluminum had to be carried in the weapon, could it be detonated with the surrounding free sea water? The result would be more explosive power per unit volume of the weapon.

TIGER CALCULATIONS

Water Shock

HMX

RDX

85%RDX 15%Al

Pentolite

Fleet

50%Al 50%H2O

TNT

Ammonium Perchlorate

Pressure (kbar)

400

300

200

100

0

Particle Velocity (m/s)

1000

2000

3000

4000
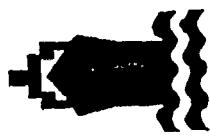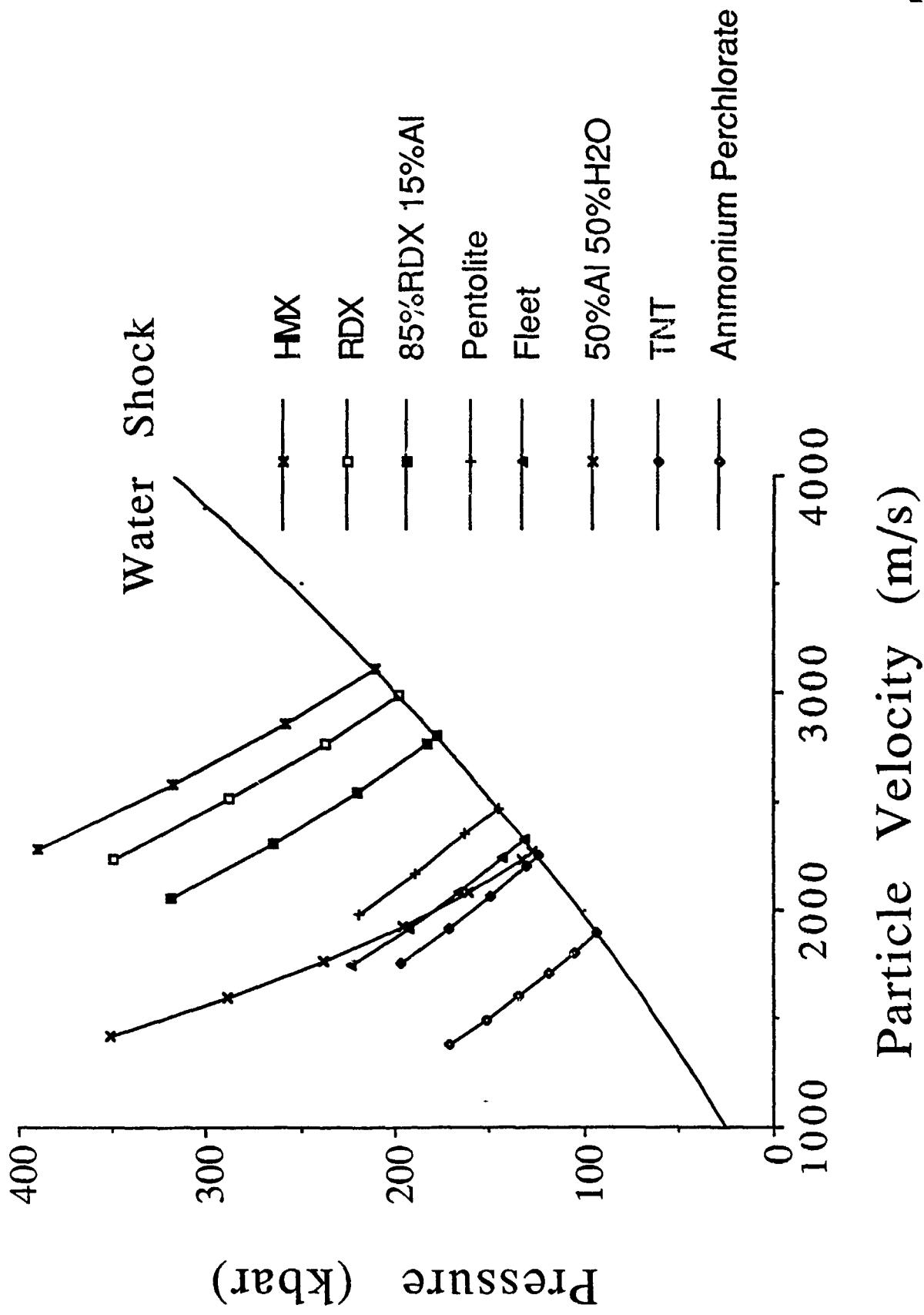
EXPLOSIVES CALCULATIONS

This chart is a tabulation of numbers from which the prior chart is graphed. In addition, the explosive density, heat of detonation, number of moles of bubble gas, and molecular weight of the bubble gas are given. These numbers will be of use in a later chart. From NSWC several shock and bubble energies relative to pentolite (50% TNT, 50% PETN) have been obtained and are tabulated.

It is to be noted that while the water shock strength of RDX/Al is lower than that of pentolite, both the shock and bubble energies are greater for the aluminized RDX. The reasons for this will be discussed later.

In the line below the Al/H_2O results is indicated the density of pure aluminum. This would be the charge density if only aluminum were carried, presuming the water were free and could be exploded with the aluminum. This is the basis for interest in steam explosions, which will be covered later.

EXPLOSIVES CALCULATIONS

Explosive	Density g/cc	Enthalpy of Detonation kcal/kg	C-J Pressure kbar	Water Pressure kbar	Water Velocity m/s	Moles Gas mol/kg	Molecular Weight Gas g-mol/g	Relative Shock Wave Energy	Relative Bubble Energy
N103 (Fleet)	1.911	-2378	222	131	2330	18.3	47.1	Classified	
Pentolite (50/50)	1.693	-1420	220	145	2470	27.0	29.5	~.0	1.0
Al/H2O (Stoic.) (2.7)	1.460	-3451	351	127	2270	27.8	27.0		
RDX/Al (85/15)	1.862	-1702	319	118	2800	23.4	36.3	1.32	1.46
RDX	1.767	-1293	349	198	2295	31.0	31.0		
AP	1.949	-984	172	98	1898	34.0	29.3		
TNT	1.630	-1058	197	124	2250	24.3	31.0	0.87	0.95
HMX	1.894	-1288	390	211	3110	30.7	31.4	1.11	1.06

Notes: Relative shock and bubble energies supplied by NSWC. Detonation calculations made with TIGER with BKW EOS and LlNL coefficients. Aluminized explosive performance overstated because of equilibrium assumption in TIGER.
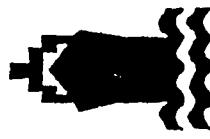
THE MYSTERIOUS EFFECT OF ALUMINUM

As mentioned, the addition of aluminum, up to a point, increases the performance of both the shock and the bubble. While the water shock pressure initially drops due to aluminum addition, which in itself would lower the shock energy, the heat of detonation is increased, leaving a more energetic bubble. There is a continual nonlinear interaction between the bubble and shock during the bubble expansion phase. A more energetic bubble expansion slows the shock decay, and there is the additional effect that a weaker initial shock is less dissipative (lower entropy rise).

A bubble containing hot particulate matter (aluminum oxide) can do more expansion work on the water than without the particulates. The simple formula at the bottom of the chart is based on the assumption that thermal equilibrium is maintained between the particles and the bubble gas. That is, as the bubble expands and cools, the particulates give up heat to the bubble gases. Here p_0 is the initial water pressure and V_0 is the initial bubble (charge) volume. The function Γ depends upon the specific heats of the gases and particulates and upon the mass fraction of the particulates, Y_s. While p_0 drops due to aluminum addition, this is more than compensated for by the fall in $\Gamma-1$. The net effect of these interactions is an increase in bubble and shock performance for modest aluminum addition.

THE MYSTERIOUS EFFECT OF Al

AN OFTEN SHOWN FIGURE (NAVORD Rept. 3760)
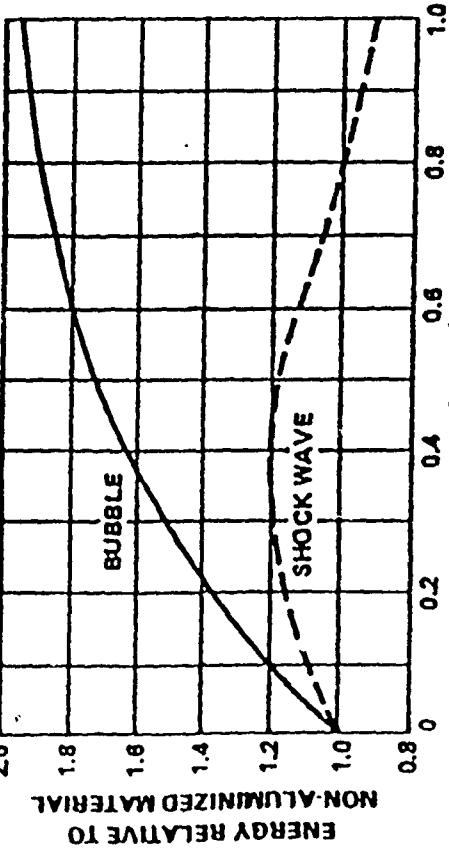
Note that at sufficiently high Al/O ratio the bubble energy must also tend downward and both must tend toward zero

- The bubble and the shock are nonlinearly connected.
- The Al addition renders the bubble expansion (the gases) nonadiabatic.
- The result is that the water shock weakens, the dissipation goes down, but the bubble is able to do more expansion work on the water, strengthening the shock.
- An approximate simple relation for the maximum P-V work that the bubble can do on the water is

$$W = p_o V_o / (\Gamma(\gamma, \gamma_s) - 1) \qquad \Gamma = (\gamma + c_{vs} * \gamma_s / c_{vg}) / (1 + c_{vs} * \gamma_s / c_{vg})$$
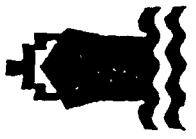
PARTICULATE EXPANSION

A little discussed effect, and one which may be of importance, is the migration of any particulate matter left in the explosion bubble. While there is oscillatory wave motion in the bubble gases, the on-average motion during the first expansion cycle is outward, dragging the particulate matter outward. As the bubble starts to recompress, particle lag may throw some particulate matter into the liquid. Depending upon the make-up of the particulates and their temperature, this may be a mechanism for late time energy release. This effect has not been studied.

Solid Products of Reaction

Bubble Boundary

$U > 0$

$U = 0$

$U < 0$

U_s

Shock

Water

Particles interact with water

Time
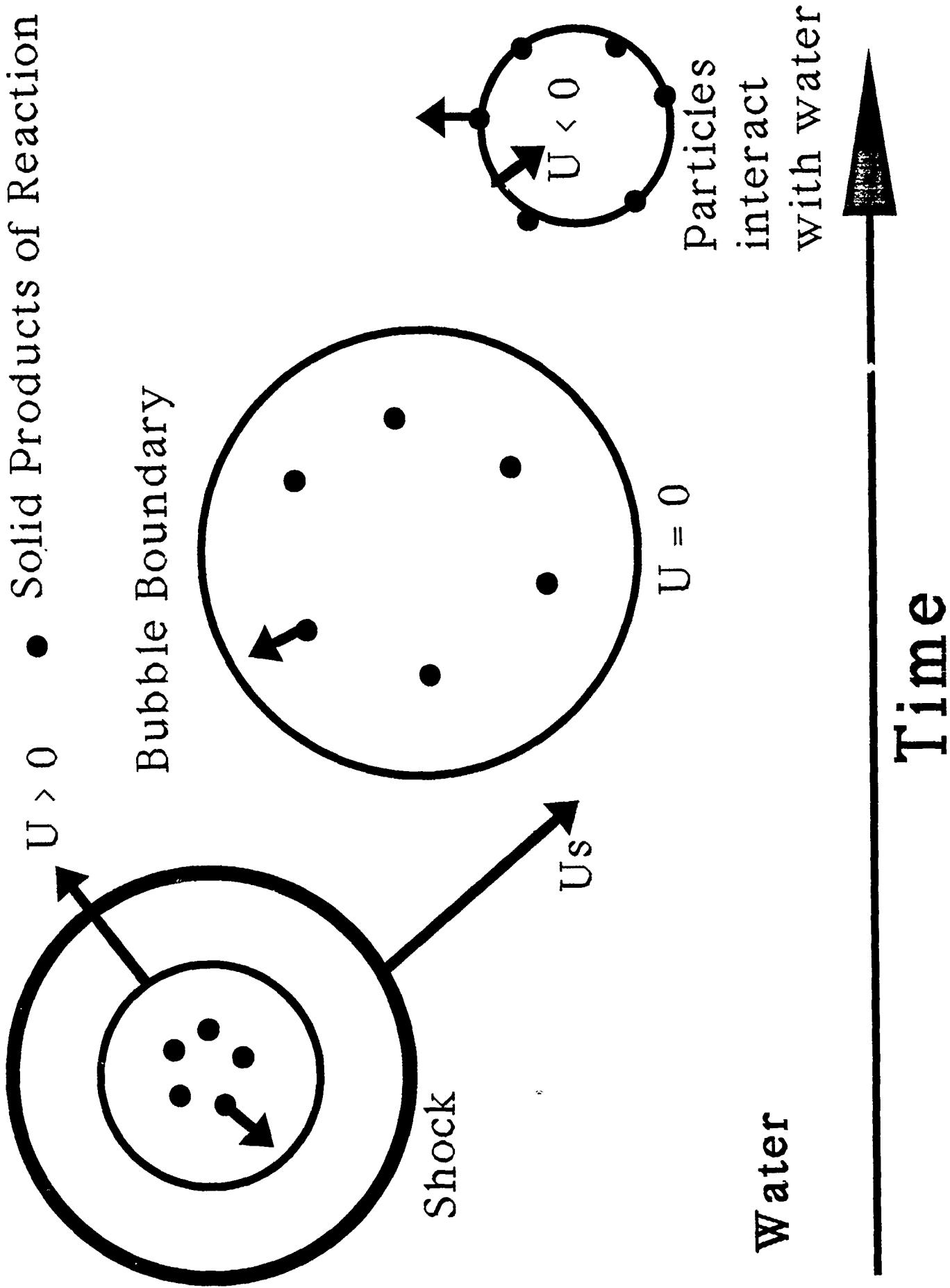
UNDERWATER EXPLOSION SCHEMATIC

This chart shows a composite of the various processes taking place during the first bubble cycle. After the shock passes into the water at B, an expansion wave, C, propagates back toward the bubble center. This propagation is going through what is called the Taylor wave, which is left by the detonation. Since the gases near the center of the Taylor wave are at rest, the expansion wave accelerates the gases toward the center. This is an intolerable condition when the wave reaches the bubble center, and the result is an outward shock reflected from the center. This shock causes a second shock at D to be propagated into the water and the process repeats. Undoubtedly the hot bubble causes some water evaporation, shown schematically at G, but the importance of this effect is unknown.

As the bubble compresses toward its first minimum it is widely believed that a fluid mechanical instability, called Rayleigh-Taylor instability, sets in causing turbulence at the bubble-water interface and greatly increasing the surface area at that interface. The turbulence generation is an energy loss mechanism, but the surface area increase should cause increased transport processes at the interface, the effects of which are not understood.

UNDERWATER EXPLOSION SCHEMATIC
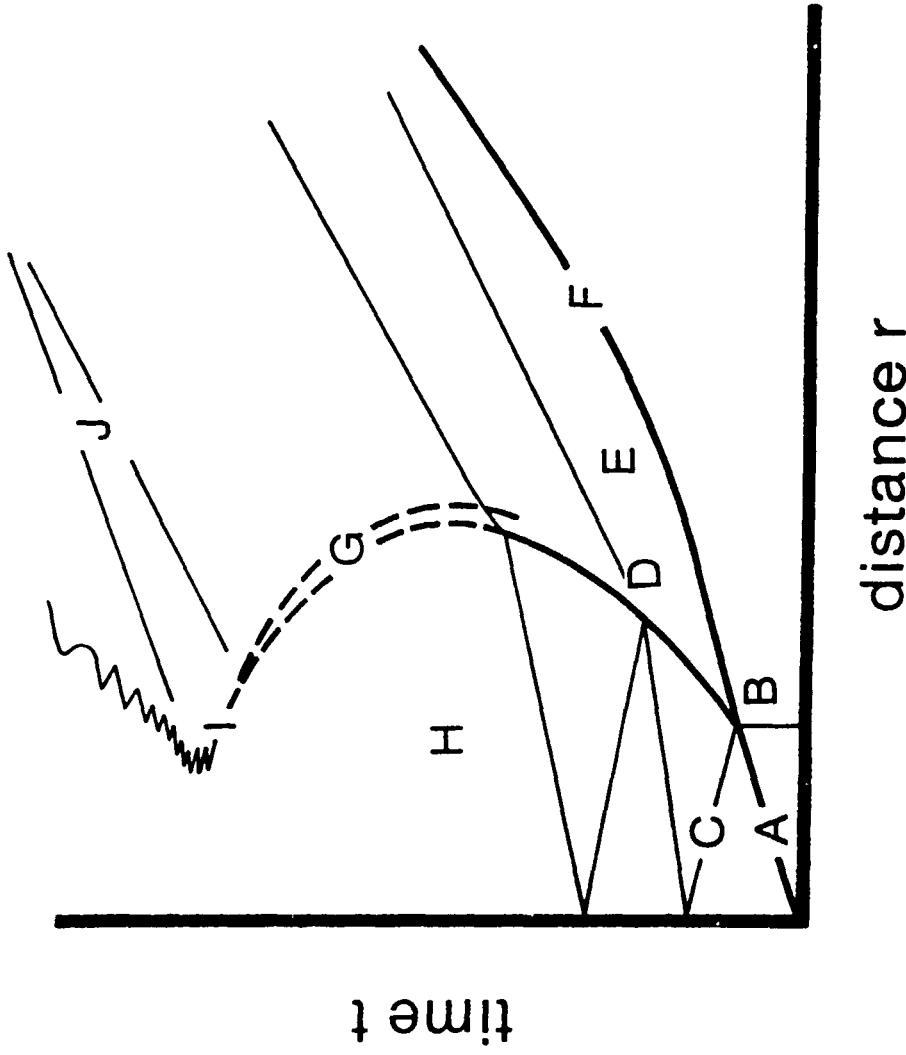
A – detonation propagation; B – detonation-water interaction ; C – gasdynamics
within bubble; D – acoustic wave interaction with the interface; E – disturbance
propagation up to shock; F – shock compression of the water; G – evaporation of
the water at the interface; H – isentropic expansion of the products; I –
interface instability near collapse; J – geometrical vs. nonlinear effects in
bubble pulse propagation

BUBBLE DYNAMICS

Some of the effects of the prior chart are shown here, for subscale detonation bubble experiments. Note the roughening of the edges near the first bubble minimum in picture 3. Computation suggests that the bubble has actually split in two at this point, and there may be an upward directed water jet in the center, which is not visible because of post-detonation debris. In any event, the edges remain rough as the bubble undergoes its second expansion.

BUBBLE DYNAMICS

(Snay, NAS-NRC Pub. 515, 1957)

Scaled conditions:
354 lb TNT
81 ft depth
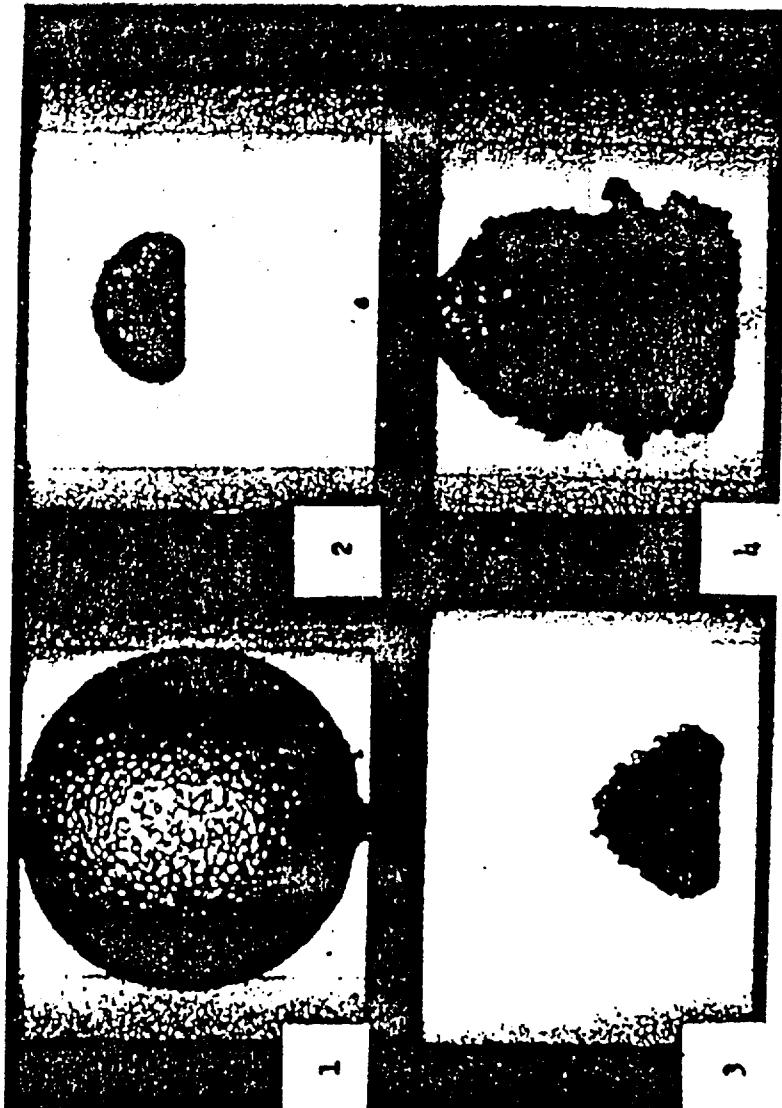
- May be jetting upward near minimum and forming two bubbles as computation suggests
- Wiggles (fractal-like) on interface after first minimum undoubtedly due to Rayleigh-Taylor instability
- Energy loss in successive cycles not fully explained
- Computation of full phenomena still in infancy

RELATIVE SHOCK WAVE AND BUBBLE ENERGIES

The Naval Surface Warfare Center has collected data from underwater explosions on 175 different tests, where the data are sufficient to extract the bubble and shock wave energies. By assuming different products of detonation in a rational way (called "arbitraries") a correlation was attempted for the energies in terms of what were found to be the strongest correlating parameters. These parameters are the heat of detonation (standard state enthalpy of detonation), the number of moles of gas, the molecular weight of the gas, and the solid phase density. Comparison was made against pentolite on both fixed volume and fixed weight bases.

The results on a fixed volume basis are summarized on the second following chart. As expected, the energies are most strongly dependent upon the heat of detonation, Q. However, there are two surprises. First, the shock wave energy depends upon the Q to only the 3/4 power, rather than the first power. Secondly, the solid density dependence is weak. Ideal detonation theory suggests that the shock pressure should be proportional to the first power of the density. Also, on a fixed volume basis the charge weight is proportional to the density. These considerations would suggest a much stronger density dependence of the energies. The reasons for this behavior are unknown.

The strong behavior with regard to Q means that estimates of this quantity are vital. However, the actual products of detonation and their equation of state are incompletely known, especially for composite, or non-ideal, explosives. Especially with metal-loaded explosives, the product state of the metal and the time scales on which the products are formed are unknown with any precision. Additionally, what state does the carbon go to - amorphous or graphite?

RELATIVE SHOCK WAVE AND BUBBLE ENERGIES

- NSWC has collected data on 175 explosives where data were sufficient to recover shock and bubble energies.

- Shock wave energy and bubble energy can <u>in first approximation</u> be estimated by peak pressure and time constant for the shock and either bubble period or maximum radius for the bubble.

- Results presented relative to Penolite (50% TNT, 50% PETN) on either a fixed weight or fixed volume basis

- Results correlated against heat of detonation, density, no. of moles gas, and molecular weight gas

- The appropriate numbers for the physico-chemical quantities are obtained by assuming different products of detonation to force best correlation. These different products are called "arbitraries" and are obtained by applying a fixed set of rules.

- The correlations are quite good and much of the scatter is probably due to the details of the different experiments (initiation method, containment, measurement method, etc.)
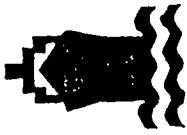
CORRELATION RESULTS

- Q=heat of detonation=$\Delta h_{det_{298}}$; N=no. moles gas; M=molecular weight gas; ρ=density; SWE_v=relative shock wave energy at constant volume; RBE_v= relative bubble energy at constant volume

- Depending on groupings of explosives by types and with different arbitraries results vary somewhat, but typical results are

$$SWE_v \propto (Q^3 * N^2 * M * \rho)^{1/4} \qquad RBE_v \propto Q * (M^{-1} * \rho)^{1/4}$$

- The dominant variable is heat of detonation. How do we get it?

- 1. The use of arbitraries is indirect and assumes perfect experiments.
  2. Use of PEP (IHTR 1340, May, 1990) assumes low pressure products.
  3. Use of TIGER assumes equations of state (EOS) adequate.
  4. Cylinder test data reduction techniques considered an art form, not science
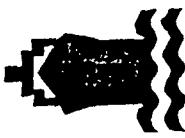
TOTAL STEAM EXPLOSIONS

When a molten substance at sufficiently high temperature encounters liquid water and if a sufficient shock impetus is applied a violent interaction can occur, involving molten substance breakup and massive steam formation in a relatively short time. This process is called a steam explosion. If the molten substance can also react with the water and release further heat and gas, the process is called a total steam explosion. In the current context, molten aluminum can strip the oxygen from water, forming aluminum oxide (condensed phase) and hydrogen gas. The process is highly energetic, and in underwater processes the water is "free".

Molten substances may be formed by thermite reactions, for example, and any shock impetus required may be provided by a secondary detonator. Since metallic substances have high density, the potential for volumetric heating value is very high. Work in this area has primarily originated from the nuclear reactor safety community, but preliminary results have been obtained with intentional explosions in mind. Work in this area is to be encouraged.

TOTAL STEAM EXPLOSIONS
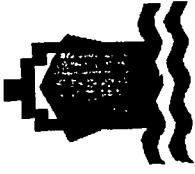
- Concept equivalent to that of airbreathing propulsion – use an oxidizer that's free – the water
- Potentially a large payoff – after more than a century of work, it is difficult to improve conventional explosives
- Volumetric energy and impulse content can be much higher than for conventional explosives
- Pulse shape for this kind of explosive *may* be more effective in terms of lethality
- The word "total" means that both the thermal energy of a metallic melt and chemical reaction with the water are to be used
- Scientific understanding is in its infancy, but the power of these explosions is known

FLUID INSTABILITIES OF INTEREST

In conventional and steam explosions there are several fluid mechanical instabilities which arise at liquid-gas interfaces. These are known as Rayleigh-Taylor, Kelvin-Helmholtz and evaporative instabilities. In an explosion bubble these processes increase the interface area considerably, cause turbulence and increase transport rates markedly. Usually near the first bubble minimum, the onset of one or more of these instabilities occurs. However, the processes have not been calculated with any detail, the importance of the them is unknown in energy budgets and the role of surface tension has not been explored. Substantial future effort is required, both computationally and experimentally, to understand the role of these instabilities in underwater explosions.

FLUID INSTABILITIES OF INTEREST

- RAYLEIGH-TAYLOR Occurs when accelerations are directed from a light fluid into a dense fluid. In explosions this occurs in dramatic fashion near a bubble minimum. Also essential in Al-water and liquid metal-steam explosions. Description requires inclusion of surface tension. Probably responsible for "unknown" loss of bubble energy during each cycle not accounted for by acoustic radiation or bubble cooling. Causes interface area to be increased markedly and generates a form of "turbulence". Has not been computed with any generality, but observed.

- EVAPORATIVE Can occur only with large evaporative mass fluxes. The liquid must be strongly superheated by the shock or by the bubble pressure undershoot on expansion. This is a form of the Landau-Darrieus instability occuring at an interface with a large density-velocity discontinuity. Importance unknown.
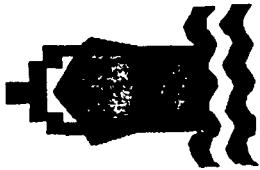
FLUID INSTABILITIES
OF INTEREST (CONT.)

- KELVIN-HELMHOLTZ The traditional cause of transition to turbulence. A migrating bubble can have a Reynolds number of the order of 10^6 to 10^7. There is also suspicion that this instability may play a role in steam explosions and chemical detonations.

- COMBINATIONS OF THE ABOVE The situation is clearly complex and some clever diagnostics are called for to unravel what may be going on near the bubble-water interface.
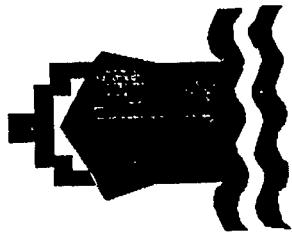
PRESSURE MEASUREMENT

One of the most widely used and practically important measurements is that of pressure. Two piezoelectric measurement devices employ the natural crystal Tourmaline or the synthetic crystal Lithium Niobate. However, these devices are pressure limited to only about 6 kbar. For close in measurement of detonation physics it is desirable to measure to the order of 300 kbar. Two promising devices involve polyvinyldifluoride (PVDF), a piezoelectric film, and ruby crystal, a pressure-dependent fluorescing substance under bombardment by green or blue light. PVDF is currently in use, but some of its properties are still under examination. Work with the ruby is still in the development phase. A critical question concerns the robustness of these newer devices in the detonation environment. However, high pressure, fast response measurements are critically needed for physical and chemical understanding of close-in detonation processes, and research into pressure measurement devices should be stressed.

PRESSURE
MEASUREMENT

- TOURMALINE, the old standby, natural crystal
  - Needs individual calibration
  - Can only go up to about 6 kbar
- LITHIUM NIOBATE, Synthetic crystal
  - Controlled manufacture, but company out of business
  - Still can only go up to about 6 kbar
- POLYVINYLDIFLUORIDE (PVDF), piezoelectric film
  - Manufactured but still under some development
  - Can go to 300 kbar needed for close-in measurements
- RUBY, fluorescent under green and blue to two red lines
  - which shift under pressure and temperature changes
  - Still in laboratory phase
  - Has been demonstrated to 100 kbar
- HYDROPHONES, state of the art but only to bars

  - NEEDS – Close in measurements are needed for code
    validation and physical/chemical understanding so
    research should continue
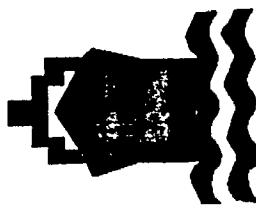
FACILITIES AND UNIVERSITIES INSTRUMENTATION

While the government and national labs are well equipped to perform solid phase detonation experiments, universities are not, because of student safety and licensing and storage requirements. The issue is whether or not the universities can make a strong contribution to a focused 6.1 research effort in underwater explosions. The universities certainly can make a strong contribution in analysis. Moreover, they are well equipped experimentally to do work in model experiments - where elements of the problem are studied in small scale experiments.

The universities are quite familiar with laser diagnostics which may be brought to bear on the problem. Shown on the third chart in this sequence are some of the optical properties of water. The more common lasers in the universities operate in the visible to which water is quite transparent. Several universities also possess high power CO_2 lasers for which water is quite opaque. Consequently, the universities can easily perform optical diagnostics and irradiation bombardment for fast heating experiments. Some universities have demonstrated ties with the labs so that joint efforts could be considered.

FACILITIES

- GOVERNMENT LABS
  - Oceans (100's of kg)
  - Quarries (10's of kg)
  - Explosion tanks (to 10kg)
  - Supercomputers
  - Detonation diagnostics
- UNIVERSITIES
  - Aquariums (non-detonable)
  - Detonation tubes (gas phase, 10's of bars)
  - Shock tubes
  - Various combustion bomb rigs
  - Supercomputers

- NATIONAL LABS
  - Explosion tanks
  - Supercomputers
 - Det. diagnostics
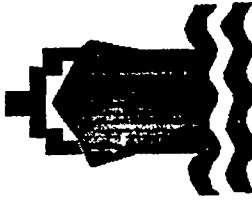
UNIVERSITIES
INSTRUMENTATION
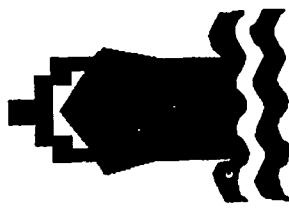
WHILE IT DEPENDS UPON WHERE ONE GOES, GENERALLY THE UNIVERSITIES ARE:

- Quite well equipped in laser diagnostics, irradiation and illumination equipment

- Some X-ray diagnostics

- Reasonably well equipped in cinephotography, image intensification and recording and data recording and processing equipment

- Adequate in chemical analysis tools under moderate conditions

     BUT

- Short on very high pressure, underwater pressure and SONAR instrumentation
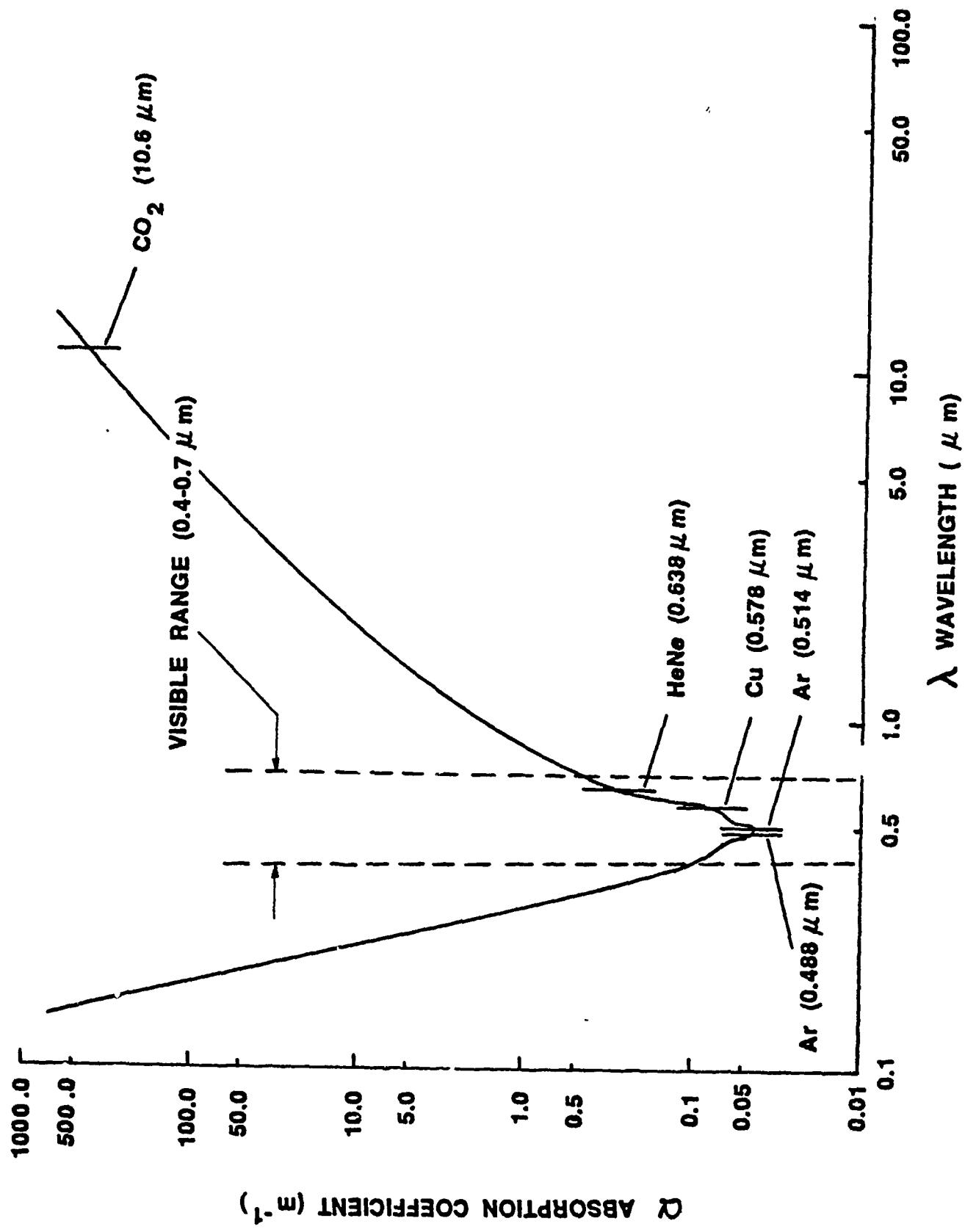
**ABSORPTION OF LIGHT IN WATER OF VARIOUS LASER LINES**

Graph labels:
- CO_2 (10.6 μm)
- VISIBLE RANGE (0.4-0.7 μm)
- HeNe (0.638 μm)
- Cu (0.578 μm)
- Ar (0.514 μm)
- Ar (0.488 μm)
- λ WAVELENGTH (μm)
- α ABSORPTION COEFFICIENT (m^{-1})

RESEARCH NEEDS
ONE POSSIBLE ROUTE TO PROGRESS

NATIONAL OR GOVERNMENT LABORATORY - UNIVERSITY COLLABORATION

Scientific Understanding

UNIVERSITY
Sub-scale experiments
Analysis and modelling

LABS
High pressure detonation
experiments
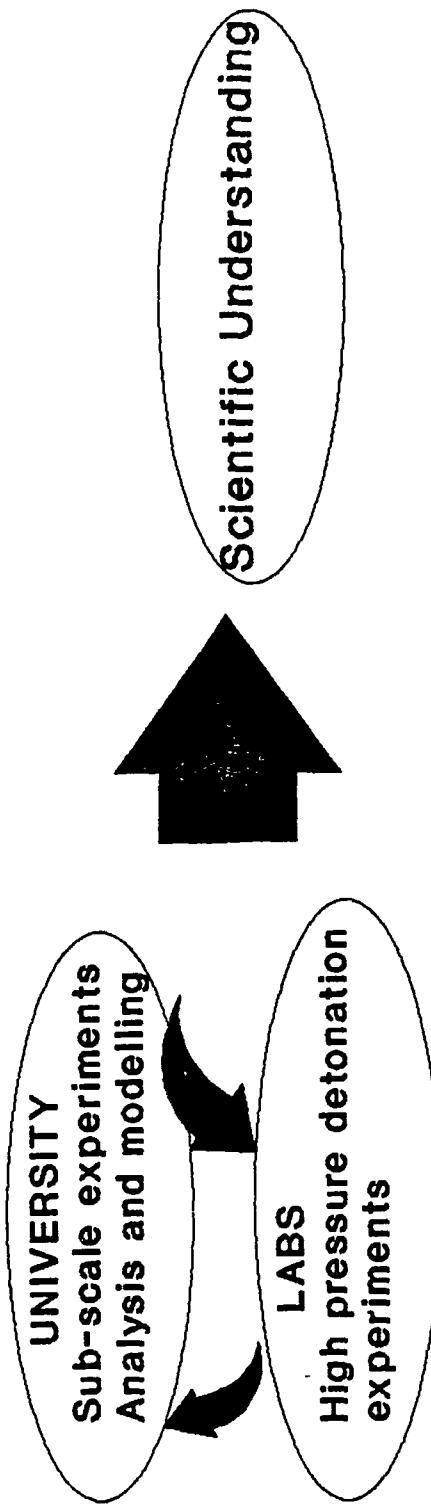
THERE ARE PRECEDENTS FOR THIS

GT
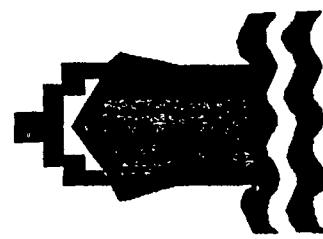
OUTSTANDING QUESTIONS AND RESEARCH NEEDS

The final three charts summarize the outstanding questions in underwater explosions and the research needs to provide the answers.

SOME QUESTIONS

FOR NON-IDEAL UNDERWATER EXPLOSIVES

- Where is the C-J plane? - What happens after and before it? - What is the effective Taylor wave? - How does the metal behave? - What is the true transmission process to the water? - What are better ingredients for this application? - Can we make metals/thermites explode underwater? - What is the role of instabilities at the bubble-water interface? - Is there turbulence in the bubble? - Where does the bubble energy go? - Can we measure jet impact forces? - Can we make *in situ* measurements? - Can we make close-in measurements? - How does the bubble develop and can we tailor it? - Can we make the explosive directional? - What is the EOS? - What are new useful diagnostics? - What can and cannot be computed? - Where did surface tension go? - What would be useful non-detonation diagnostics? - Are there any new useful detonation diagnostics?
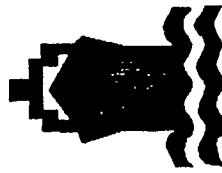
RESEARCH NEEDS*

- Comprehensive modeling and clever verification experiments for the underwater explosion process of non-ideal explosives including the following effects:
  - Early and late time chemistry and chemical kinetics with adequate data base for the EOS of the detonation products with special emphasis on the metal behavior
  - Multiple phase flow with mass and heat transport and metal combustion, agglomeration, shattering and metal oxide condensation and carbon clustering
  - Bubble dynamics including the three dimensional interface instabilities, realistic evaporation rates, condensed phase interaction with the water, late time reactions, realistic transmission through the case, surface tension effects and three dimensional effects near targets
  - Realistic gas dynamics within the bubble including wave motion and gravity

*Remain much like those generated at the Atlanta workshop
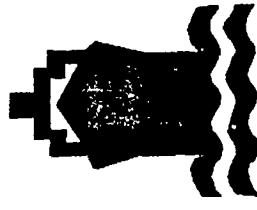
RESEARCH NEEDS
(CONTINUED)

- Search for other ingredients such as B, Fl, Zr, HAP to increase detonation energy using realistic constituitive relations which may either be measured or fundamentally computed

- Continue research on diagnostic methods for close-in and in situ measurements with fast response

- Determine feasibility of metal/thermite – water explosions as underwater weaponry

- Use clever non-detonation experiments and analysis for study of several "unit" processes contributing to the overall explosion process, e.g.

  - Vertical shock tube experiments at a gas water interface for evaporation studies

  - Non-detonation (deflagration) bubble experiments and analysis using simple compositions and variable surface tension

  - Melting/exploding wire – water explosion processes